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# Influence of Cutting Parameters on Tool Life and Surface Roughness in CNC Turning of C65 Steel: An ISO 3685-Based Experimental Study

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## Abstract:
This study experimentally investigates the effects of machining parameters on tool life and surface roughness during the CNC turning of C65 steel under dry cutting conditions. The study aims to determine the optimal machining parameters, namely cutting speed, feed rate, and depth of cut, to enhance machining performance while maintaining acceptable surface quality and extending tool life. Achieving these objectives is expected to improve manufacturing productivity and reduce overall machining costs.
A structured L9 orthogonal array comprising nine machining trials was employed to systematically investigate the selected machining conditions while minimising the number of experimental runs. Tool life was evaluated in accordance with ISO 3685:1993 using a flank wear criterion of VB = 0.3 mm, whereas surface roughness (Ra) was measured to assess the quality of the machined surface. The turning experiments were conducted under dry cutting conditions on a CNC lathe using single-point carbide inserts.
The results revealed that cutting speed was the most influential factor affecting tool life. The longest tool life of 4.6 min was achieved at 1000 rpm, 0.22 mm/rev feed rate, and 2.0 mm depth of cut, whereas the shortest tool life of 0.9 min occurred at 1700 rpm

and 0.30 mm/rev feed rate. Surface roughness was primarily governed by feed rate, lower feed rates producing significantly smoother surfaces. The findings demonstrate that the appropriate selection of machining parameters can substantially improve tool performance and surface finish during CNC turning of C65 steel, providing practical guidance for industrial machining applications.
**Keywords:** C65 Steel, CNC turning, Tool life, Surface roughness, ISO 3685:1993, Flank wear, Dry machining.

# تأثير ظروف القطع على عمر الأداة وخشونة السطح أثناء خراطة فولاذ C65 باستخدام ماكينات التحكم الرقمي بالحاسوب:(CNC) دراسة تجريبية وفق ISO 3685

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**الملخص:**

تبحث هذه الدراسة بشكل تجريبي تأثير معاملات التشغيل على عمر الأداة وخشونة السطح أثناء خراطة الفولاذ عالي الكربون C65 باستخدام آلة خراطة ذات التحكم الرقمي بالحاسوب (CNC) تحت ظروف التشغيل الجاف. وهدفت الدراسة إلى تحديد القيم المثلى لمعاملات التشغيل، والمتمثلة في سرعة القطع، ومعدل التغذية، وعمق القطع، بهدف تحسين أداء عملية التشغيل، والحفاظ على جودة سطح مناسبة، وإطالة عمر الأداة بما يسهم في زيادة الإنتاجية وخفض تكاليف التشغيل.

أُستخدمت مصفوفة تجريبية متعامدة من النوع L9 تضم تسع تجارب تشغيلية لدراسة تأثير ظروف التشغيل المختارة بصورة منهجية، مع تقليل عدد التجارب المطلوبة. وتم تقييم عمر الأداة وفقًا للمواصفة القياسية ISO 3685:1993 باستخدام معيار التآكل الجانبي للأداة (VB = 0.3 mm) ، في حين تم قياس خشونة السطح (Ra) لتقييم جودة السطح المشغل. وأُجريت تسع تجارب خراطة باستخدام أداة قطع كربيد أحادية الحد القاطع على

http://www.doi.org/10.62341/istj-vol39-1-kw22

مخرطة CNC عند مستويات مختلفة من معاملات التشغيل. أظهرت النتائج أن سرعة القطع كانت العامل الأكثر تأثيرًا في عمر الأداة، حيث تحقق أطول عمر للأداة بلغ 4.6 دقيقة عند سرعة دوران 1000 دورة/دقيقة، ومعدل تغذية 0.22 مم/دورة ، وعمق قطع 2.0 مم ، في حين سُجل أقصر عمر للأداة، والبالغ 0.9 دقيقة، عند سرعة دوران 1700 دورة/دقيقة ومعدل تغذية 0.30 مم/دورة. كما أوضحت النتائج أن معدل التغذية كان العامل الأكثر تأثيراً في خشونة السطح، حيث أدت معدلات التغذية المنخفضة إلى الحصول على أسطح أكثر نعومة بصورة ملحوظة. وتؤكد نتائج الدراسة أن الاختيار الأمثل لمعاملات التشغيل يمكن أن يُحسن بشكل كبير من عمر الأداة وجودة السطح المشغل أثناء خراطة فولاذ C65 باستخدام آلات CNC، مما يوفر إرشادات عملية لتحسين كفاءة عمليات التشغيل الصناعية.
**الكلمات المفتاحية:** فولاذ عالي الكربون C65؛ الخراطة باستخدام CNC؛ عمر الأداة؛ خشونة السطح؛ ISO 3685؛ التآكل الجانبي للأداة؛ التشغيل الجاف.

## 1. Introduction

Tool wear is one of the most critical challenges in machining operations, as it directly affects dimensional accuracy, surface integrity, production cost, and overall manufacturing efficiency (Soori & Arezoo, 2022). Progressive tool degradation leads to increased cutting forces and temperatures, unstable cutting conditions, deterioration of surface quality, and frequent tool replacement. Consequently, productivity decreases while machining costs increase. Accordingly, improving tool life has become a fundamental objective in modern manufacturing systems aiming to achieve both economic efficiency and high product quality (Lalwani et al., 2008; Abidi et al., 2021).

The study of tool life dates back to early machining research, most notably Taylor’s tool life equation, which established the inverse relationship between cutting speed and tool life (Altounsi et al., 2025). Although cutting speed remains the dominant factor influencing tool wear, subsequent investigations have confirmed

http://www.doi.org/10.62341/istj-vol39-1-kw22

that feed rate, depth of cut, workpiece material, cutting environment, and tool geometry and coating also significantly influence wear mechanisms and tool performance (Duc et al, 2020; Hu et al, 2024; Hoier, 2019). Collectively, these parameters govern wear evolution and tool lifespan under different machining conditions.

Flank wear is the most widely adopted criterion for tool failure assessment due to its progressive development and direct impact on dimensional accuracy and surface quality. To standardise tool life evaluation, ISO 3685:1993 defines a standardised methodology for tool life testing in turning operations using a single point cutting tool. A flank wear criterion of VB = 0.3 mm is recommended as the tool life end point, enabling consistent comparison of experimental results across different studies.

Surface roughness is another key indicator of machining quality, as it significantly influences fatigue strength, wear resistance, frictional behavior, and functional performance of mechanical components. Achieving low surface roughness is therefore essential for ensuring product reliability and extending service life. Numerous studies have shown that cutting parameters, particularly cutting speed, feed rate, and depth of cut, strongly affect surface finish, with feed rate typically identified as the most influential factor due to its direct correlation with feed marks on the machined surface (Asiltürk & Akkuş, 2011; Rao et al., 2013).

Previous experimental investigations have extensively examined the relationship between machining parameters and turning performance. Lalwani et al. (2008) reported that increasing feed rate and depth of cut leads to higher cutting forces and worse surface quality, whereas higher cutting speeds may improve surface finish under suitable conditions. Similarly, Asiltürk and Akkuş (2011) identified feed rate as the dominant factor affecting surface roughness, followed by cutting speed. These findings were further confirmed by Rao et al. (2013) through statistical analysis, demonstrating the predominant influence of feed rate over other parameters. These studies highlight that proper selection of

http://www.doi.org/10.62341/istj-vol39-1-kw22

machining parameters is essential to achieve an optimal balance between productivity, surface quality and tool life.

Despite extensive research on machining optimisation, most studies have focused separately on either surface roughness improvement or tool life optimisation using Taguchi-based approaches (Sultan et al., 2021; Rathod et al., 2021; Singaravel et al., 2016). Moreover, limited attention has been given to dry turning of C65 steel under ISO 3685:1993 tool life criteria (VB = 0.3 mm) while simultaneously evaluating surface roughness. This represents a clear research gap in understanding the coupled effect of cutting parameters on both tool wear and surface integrity under standardised conditions.

To address this gap, the present study investigates the effects of cutting speed, feed rate, and depth of cut on tool life and surface roughness during dry turning of C65 steel. Tool life is evaluated in accordance with ISO 3685:1993, while surface roughness is measured as a quality response of the machining process. The study aims to provide a comprehensive understanding of the interaction between machining parameters and performance responses to support process optimisation in industrial applications.

## 2. Experimental Work

The experiments were conducted using single point carbide cutting tools under a controlled machining environment on a CNC machine. Three levels of machining parameters were selected based on an L9 orthogonal array design, ensuring a reduced number of experiments while maintaining the reliability of statistical analysis. The experimental data were analysed using Minitab 16 software.

C65 steel, as shown in Figure (1) was selected as the workpiece material due to its wide industrial applications in components requiring high strength, hardness, and wear resistance, such as cutting tools, springs, gears, shafts, and other heavy duty mechanical and automotive parts, making it a suitable material for investigating the effects of cutting parameters on tool life and surface roughness during CNC turning. For the experimental work,

http://www.doi.org/10.62341/istj-vol39-1-kw22

nine cylindrical specimens each with a diameter of 60 mm and a length of 100 mm, were prepared. All specimens were cut from the same rod to ensure consistency and reliability of the experimental results. A schematic drawing illustrating the dimensions of the test specimen is presented in Figure (2).

Fig.1: A Representative Specimen Used for the Experimental Tests

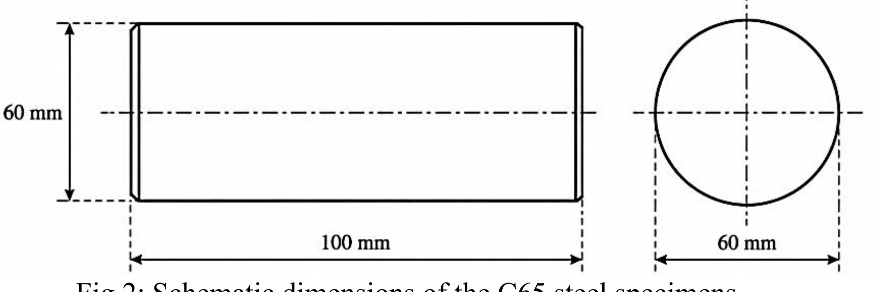


Fig.2: Schematic dimensions of the C65 steel specimens

The chemical composition of the workpiece material was determined using an atomic emission spectrometer at the Libyan Advanced Occupational Center for Welding Technologies prior to machining. The measured elemental composition confirmed that the workpiece material was C65 high carbon steel. As presented in Table 1, the chemical composition consists primarily of 0.649 wt.% carbon, 0.595 wt.% manganese, and 0.349 wt.% silicon, while iron constitutes the rest of the specimen. The concentrations of the remaining elements were found to be within the typical range for C65, confirming the material classification.

http://www.doi.org/10.62341/istj-vol39-1-kw22

**Table 1: Chemical Composition of C65 Steel.**

| Element | C | Mn | Si | P | S | Cr | Ni | Mo | Cu |
|---|---|---|---|---|---|---|---|---|---|
| Wt.% | 0.649 | 0.595 | 0.349 | 0.012 | 0.012 | 0.154 | 0.1168 | 0.036 | 0.108 |

## 2.1. Cutting Tool

VCMT 11 03 02-F carbide inserts, as shown in Figure (3a), were used in the machining experiments. The inserts were selected because their TiAlN coating provides excellent wear resistance and thermal stability under dry machining conditions, while their 35° diamond geometry reduces cutting forces and facilitates efficient chip evacuation, making them suitable for machining high carbon C65 steel. Each insert was replaced once it reached the predefined flank wear limit before proceeding to the next test. The inserts were mounted on a Sandvik Coromant CNC turning tool holder shown in Figure (3b), the insert performs the material removal during machining.


Fig.3: (a) VCMT 11 03 02-F indexable carbide insert; (b) Sandvik Coromant CNC external turning tool holder.

The insert features a 35° diamond shaped geometry and a 7° clearance angle, providing low cutting forces, effective chip control, and improved surface finish.A schematic illustration of the insert geometry and its principal angles is presented in Figure 4.

http://www.doi.org/10.62341/istj-vol39-1-kw22

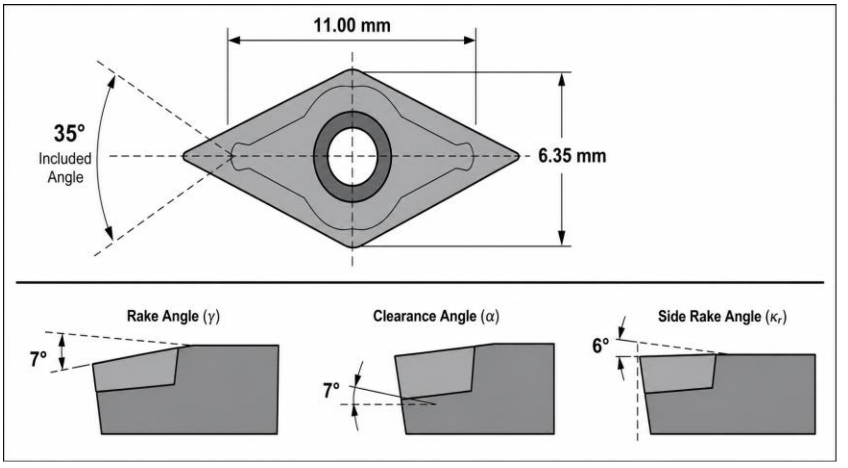

Fig.4: A schematic of the VCMT 11 03 02-F carbide insert with its principal cutting angles.

**2.2 Selection of Cutting Parameters**

After selecting the workpiece material and cutting tool type, the machining parameters were determined based on the tool manufacturer's recommendations for the VCMT carbide insert and machining conditions commonly reported in the literature for turning high carbon steels (Sandvik Coromant, 2024; Lalwani et al., 2008). Tool life evaluation was performed in accordance with ISO 3685:1993 using a flank wear criterion of VB = 0.3 mm (ISO, 1993). This selection ensured that the experimental conditions closely represented realistic industrial machining environments while maintaining standardised tool-life assessment.

All machining experiments were conducted at the Libyan Higher Technical Center for Training and Production using a Hwacheon Hi-ECO 31A CNC lathe as shown in Figure 5. The machine is equipped with a FANUC CNC controller and has a maximum turning diameter of approximately 350 mm, a maximum turning length of 500 mm, and a spindle speed range of 50–4,000 rpm. These specifications provide the stability, precision, and repeatability required for controlled machining experiments. The use of CNC technology ensured accurate control of the cutting parameters while minimising variability associated with manual machining, thereby improving the reliability and consistency of the experimental results. All tests were performed under dry cutting conditions, without the use of cutting fluids, to eliminate the effects of cooling and lubrication on the cutting process. This approach enabled a more accurate evaluation of the influence of cutting speed, feed rate, and depth of cut on tool wear progression, tool life, and surface roughness, ensuring that the observed performance was solely attributed to the selected machining parameters.


Fig.5: CNC Turning Machine Used in the Experiments

Three levels were selected for the main cutting parameters, namely cutting speed, feed rate, and depth of cut, in order to investigate their effects on cutting tool life and surface roughness during CNC turning operations. The parameter levels were determined based on the suitable machining range for C65 steel and the recommendations provided by the cutting tool manufacturer, as presented in Table (2).

**Table 2: Cutting Conditions and Levels of Cutting Parameters.**

| Cutting Parameters | Unit | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|
| Cutting Speed | rpm | 1000 | 1300 | 1700 |
| Feed Rate | mm/rev | 0.15 | 0.22 | 0.30 |
| Depth of Cut | mm | 1.5 | 2.0 | 2.5 |

**3. Tool Life Measurement**

The cutting tool life was evaluated using a metallurgical microscope based on ISO 3685:1993 for tool wear assessment. According to this

http://www.doi.org/10.62341/istj-vol39-1-kw22

standard, tool failure is defined when the flank wear (VB) reaches a value of 0.3 mm, which is considered the minimum limit of effective tool life.

Tool wear was monitored using an FL8000 Upright Metallurgical Optical Microscope, as shown in Figure 6. The microscope is equipped with 5×, 10×, 40×, and 60× objectives, providing a magnification range of 50×–600×, and features a 2 µm focusing resolution, enabling clear observation of flank wear progression. Flank wear was measured periodically during the machining experiments to track the evolution of tool degradation throughout the cutting process. The ISO 3685:1993 standard was adopted as the failure criterion, considering the tool unfit for further use once the flank wear reached 0.3 mm.

Fig.6: Metallurgical Microscope Used for Measuring Cutting Tool Wear

The surface roughness (Ra) of the machined specimens was measured using an SRT-6210 Surface Roughness Tester, as shown in Figure 7. The instrument has a measurement range of 0.05–10.0 µm (Ra) and 0.1–50 µm (Rz), with a resolution of 0.01 µm and an accuracy of ±10% of the measured value.

http://www.doi.org/10.62341/istj-vol39-1-kw22


Fig.7: Surface Roughness Measurement Device

Surface roughness measurements were performed after the cutting tool reached the prescribed flank wear criterion (VB = 0.3 mm). For each specimen, three measurements were taken at different locations, and the average value was calculated to improve measurement reliability.

**3- Results and Discussion**

Table (3) presents the results of the experimental study conducted to analyse the effect of the main cutting parameters in the turning process on cutting tool life. These parameters included cutting speed (rpm), feed rate (mm/rev), and depth of cut (mm). Nine different experiments (T1–T9) were carried out according to a structured experimental design, where the operating parameter levels were varied and the tool life was measured based on the machining time required to reach the allowable wear limit.

The selected parameter levels were established based on the technical recommendations of the carbide cutting tool manufacturer, the machining characteristics of the C65 high carbon steel workpiece, technical consultations, and brainstorming sessions with

http://www.doi.org/10.62341/istj-vol39-1-kw22

experienced engineers and machining specialists at the Libyan Higher Technical Center for Training and Production.

**Table 3: Tool Life Results**

| Experiment No. | Cutting Speed (rpm) | Feed Rate (mm/rev) | Depth of Cut (mm) | Tool Life (min) | Ra (µm) |
|---|---|---|---|---|---|
| T1 | 1000 | 0.15 | 1.5 | 2.0 | 1.57 |
| T2 | 1000 | 0.22 | 2.0 | 4.6 | 4.15 |
| T3 | 1000 | 0.30 | 2.5 | 2.4 | 5.02 |
| T4 | 1300 | 0.15 | 2.0 | 3.1 | 1.76 |
| T5 | 1300 | 0.22 | 2.5 | 2.5 | 3.18 |
| T6 | 1300 | 0.30 | 1.5 | 1.8 | 6.88 |
| T7 | 1700 | 0.15 | 2.5 | 1.9 | 2.02 |
| T8 | 1700 | 0.22 | 1.5 | 1.6 | 3.02 |
| T9 | 1700 | 0.30 | 2.0 | 0.9 | 4.43 |

### 3.1 Discussion of Tool Wear Results

The experimental results showed that the highest tool life was obtained in experiment T2, reaching 4.6 min. This condition corresponds to a relatively low cutting speed (1000 rpm), a medium feed rate (0.22 mm/rev), and a depth of cut of 2 mm. The improved tool life can be attributed to stable cutting conditions that reduce heat generation and cutting forces, thereby slowing down tool wear progression.

Although T2 has a higher feed rate than T1, it still provides longer tool life due to more efficient chip formation. In T1, the lower feed produces a thinner chip, which increases rubbing and tool–workpiece contact time. This leads to higher friction, greater heat concentration at the cutting edge, and faster flank wear. In contrast, T2 produces a thicker chip that reduces contact time and improves chip evacuation, resulting in lower friction and reduced heat accumulation. Consequently, tool wear develops more slowly, leading to higher tool life based on the ISO 3685 criterion (VB = 0.3 mm). On the other hand, experiment T9 recorded the lowest tool life (0.9 min) under high cutting speed (1700 rpm), high feed rate (0.30 mm/rev), and a depth of cut of 2 mm. This indicates that increasing

http://www.doi.org/10.62341/istj-vol39-1-kw22

cutting speed and feed rate significantly accelerates tool wear due to higher thermal and mechanical loads acting on the cutting edge.

Figure (8) presents the relationship between cutting time (min) and tool wear (mm) for experiment T2 in order to determine tool life during the machining process.

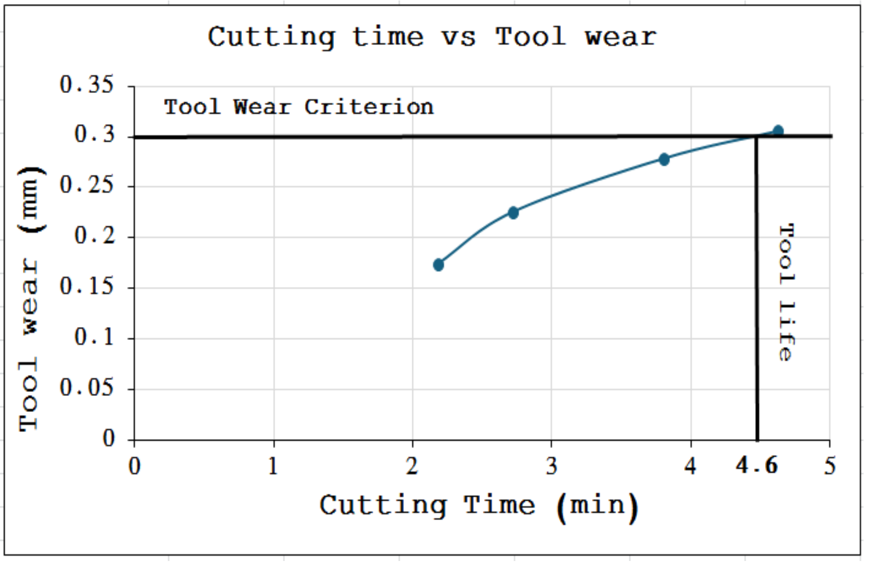


Fig.8: The relationship between cutting time and tool wear for experiment T2

The graph shows that the wear rate increased gradually with machining time. Tool wear started at approximately 0.174 mm at a cutting time of 2.18 minutes and continued increasing progressively until it reached nearly 0.306 mm at 4.6 minutes, which represents the tool life under the selected machining conditions.

Figure (9) shows the microscopic analysis of the cutting tool surface after machining in experiment T2. The results indicate gradual tool wear under stable cutting conditions, starting at 0.174 mm (174 µm) after 2.18 min and increasing steadily until reaching the ISO 3685 flank wear limit after 4.6 min.

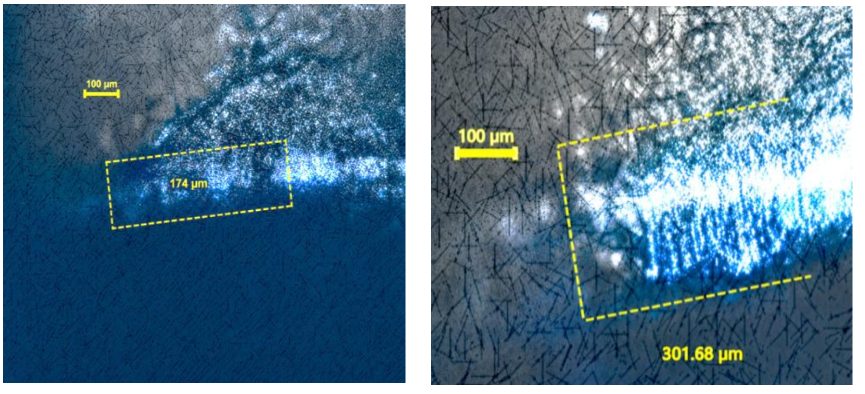


Fig.9: The microscopic analysis of the cutting tool in experiment T2.

Figure (10) presents the variation of tool wear with cutting time under severe machining conditions in experiment T9. Tool wear started at approximately 0.17 mm (170 µm) at a cutting time of 0.2 minutes, increased rapidly to nearly 250 µm at 0.45 minutes, and eventually reached the allowable wear limit of 300 µm at approximately 0.94 minutes. This limit is referred to as the tool wear criterion and is used to determine the point at which the tool becomes unsuitable for further machining.

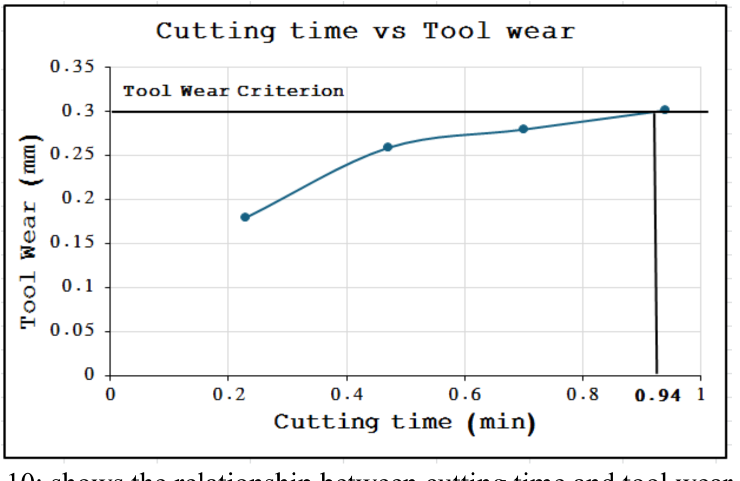


Fig.10: shows the relationship between cutting time and tool wear for experiment T9.

http://www.doi.org/10.62341/istj-vol39-1-kw22

Figure (11) shows the microscopic visual analysis of the cutting tool surface after machining in experiment T9. The figure reveals severe and rapid wear after a very short cutting time of 0.94 minutes, with wear values approaching 170 µm at the initial stage. The steep wear progression indicates rapid deterioration of the cutting tool, which can be attributed to unsuitable machining conditions and excessive thermal and mechanical loads acting on the cutting edge.

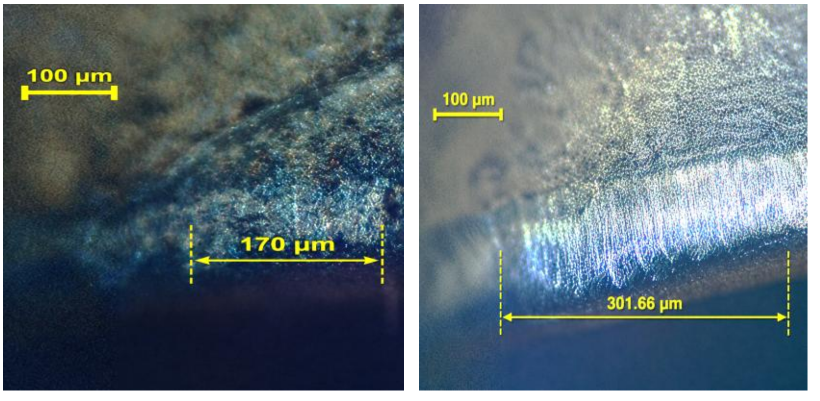


Fig.11: The microscopic analysis of the cutting tool in experiment T9.

**3.2 Discussion of Surface Roughness Results**

The contour plot shown in Figure (12) presents the combined influence of cutting speed and feed rate on surface roughness (Ra) during machining. The results indicate that feed rate is the most influential parameter affecting surface roughness. An increase in feed rate from 0.15 to 0.30 mm/rev results in a noticeable increase in Ra from approximately 2–3 µm to 5–6 µm or higher, indicating a clear deterioration in surface quality.

Cutting speed exhibits a secondary effect on surface roughness. At lower feed rates, increasing cutting speed leads to a slight reduction in Ra, particularly within the medium speed range (≈1300–1500 rpm), where improved surface finish is observed. This behavior is associated with improved cutting stability and reduced built-up edge formation at higher cutting speeds. However, at higher feed rates,

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the influence of cutting speed becomes negligible, with Ra remaining consistently high across the investigated speed range.

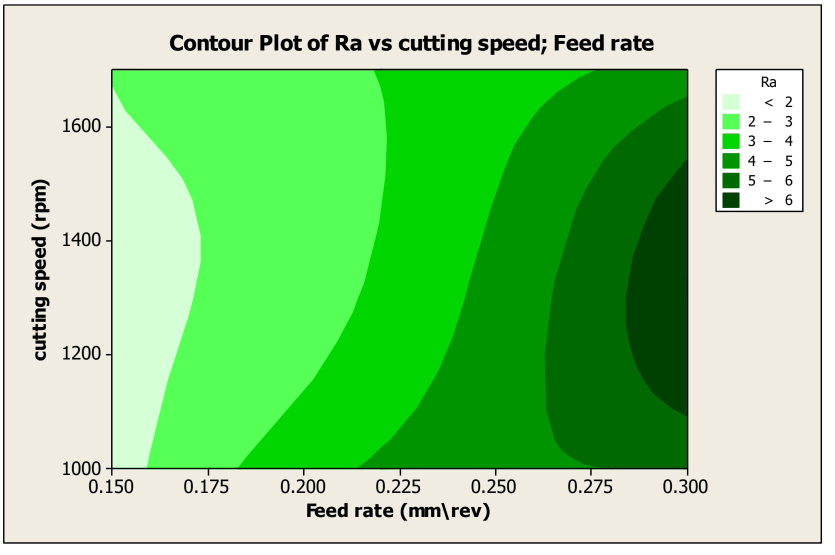


Fig .12: The influence of cutting speed and feed rate on surface roughness

Overall, minimum surface roughness is obtained at low feed rate combined with moderate to high cutting speed, whereas maximum Ra values are observed at high feed rate irrespective of cutting speed.

**4. Limitations of the Study**

This study was limited to evaluating the effects of cutting speed, feed rate, and depth of cut on tool life and surface roughness during CNC turning of C65 steel. Other influential factors, such as tool coating, cutting environment, and tool geometry, were not considered. In addition, material characterisation was limited to chemical composition analysis, while mechanical properties were not experimentally evaluated. Future research should investigate a wider range of machining conditions and include comprehensive material characterisation to improve the reliability and applicability of the findings.

## 5. Conclusion

This study experimentally investigated the effects of cutting speed, feed rate, and depth of cut on tool life and surface roughness during CNC turning of C65 steel using L9 orthogonal array design. Tool wear was evaluated according to the ISO 3685:1993 standard using a flank wear criterion of VB = 0.3 mm.

The results demonstrated that cutting speed and feed rate are the dominant machining parameters influencing tool performance and surface quality. Lower cutting speeds significantly improved tool life by reducing thermal and mechanical loads on the cutting edge, whereas higher feed rates accelerated wear progression and increased surface roughness. The optimum machining condition identified in this study was 1000 rpm spindle speed, 0.22 mm/rev feed rate, and 2.0 mm depth of cut, resulting in the maximum tool life of 4.6 min while maintaining acceptable surface roughness.

Microscopic examination confirmed gradual wear development under moderate machining conditions and rapid flank wear growth under severe cutting conditions. Surface roughness analysis further indicated that feed rate is the most influential parameter affecting surface finish, whereas higher cutting speeds improved surface quality when combined with lower feed rates.

The findings of this study provide practical guidance for selecting machining parameters in industrial CNC turning operations involving C65 steel. Future research may incorporate additional machining responses, such as cutting forces, cutting temperature, power consumption, and multi-objective optimisation techniques, to establish a more comprehensive optimisation framework.

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**Conflict of Interest**
The authors declare that they have no conflict of interest.

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